Amendments to the Specification

Please replace the paragraph on page 1, line 16, beginning "This application claims priority" with the following amended paragraph:

This application is related to the following applications: United States Application Serial No. 09/452,749 entitled "Permanent Readout Superconducting Qubit" filed December 1, 1999; United States Application Serial No. 09/872,495 entitled "Quantum Processing System And Method For A Superconducting Phase Qubit" filed June 1, 2001; United States Application Serial No. ~~0/025,848~~ <u>10/025,848</u> entitled "Finger Squid Qubit Device" filed December 17, 2001; United States Application Serial No. ~~60/341,794~~ <u>60/341,974</u>, entitled "Characterization And Measurement of Superconducting Structures" filed December 18, 2001; United States Application Serial No. 60/349,663, entitled "Two Junction Phase Qubit" filed January 15, 2002; United States Application Serial No. ~~60/383,597~~ <u>60/374,261</u> entitled "Resonant Controlled Qubit System" filed April 20, 2002, each of which is incorporated herein by reference in their entirety.

Please replace the paragraph on page 3, line 23, beginning "Materials that exhibit superconducting properties" with the following amended paragraph:

Materials that exhibit superconducting properties are attractive candidates for quantum computing applications, since the quantum behavior of the Bose condensates (Cooper pairs) at Josephson junctions have macroscopically observable consequences. Indeed, recently, several designs of a superconducting qubit have been proposed and tested. See, for example, Nakamura *et al.*, 1999, *Nature* 398, p. 786; Friedman *et al.*, 2000, *Nature* 406, p. 43; and van der Wal *et al.*, 2000, *Science* 290, p. 773, which are hereby incorporated by reference in their entireties. The qubits described in these ~~reference~~ <u>references</u> demonstrate the existence of qubits having potential energy states. The qubits described in these ~~reference~~ <u>references</u> are not coupled and they are not controlled in a scalable manner. Therefore, the qubits described in these references do not satisfy all the requirements for universal quantum computing put forth by DiVincenzo.

Please replace the paragraph on page 10, line 8, beginning "Another embodiment of the present invention" with the following amended paragraph:

Another embodiment of the present invention provides a method for controlling a qubit. The method comprises providing a superconducting qubit that is characterized by a critical frequency correlated with the energy difference between the basis states of the qubit. In the method a tunable resonant circuit is controllably coupled to the qubit for some duration t_1. The tunable resonant circuit has a resonant frequency that correlates with the critical frequency of the superconducting qubit[[,]].

Please replace the paragraph on page 4, line 10, beginning "The quantum mechanical properties" with the following amended paragraph:

The quantum mechanical properties of a qubit are easily affected by interactions between the qubit and the environment (*e.g.*, other systems). Yet quantum computing requires that the qubit be isolated from such interactions so that the state of the qubit can coherently evolve in accordance with a quantum gate that is applied to the qubit. Despite the requirement for isolation so that the qubit can evolve, universal quantum computing still requires some control over (interaction with) the qubit so that fundamental operations such as qubit initialization, gate application, and qubit state measurement can be effected. This apparent contradiction between the need for isolation and the need for control over the ~~quibt~~ qubit is a direct result of the quantum behavior of qubits.

Please replace the paragraph on page 12, line 14, beginning "In accordance with the present invention" with the following amended paragraph:

In accordance with the present invention, a circuit for controlling a qubit includes a superconducting qubit having a qubit frequency between approximately 0.8 GHz and 40 GHz and a resonant control system that is characterized by a resonant frequency. This resonant frequency is a function of an effective capacitance of the resonant control system as well as an effective inductance of the resonant control system. Further, at least one of the effective capacitance and the effective inductance is adjustable so that the resonant frequency of the resonant control system can be

tuned to a predetermined resonant frequency. The circuit further includes a superconducting mechanism coherently coupled to the ~~supreconducting~~ superconducting qubit and the resonant control system. The superconducting mechanism is used to coherently couple the superconducting qubit and the resonant control system together. In some embodiments, the resonant control system is superconducting.

Please replace the paragraph on page 19, line 13, beginning "In an embodiment of the present invention" with the following amended paragraph:

In an embodiment of the present invention, the ~~supeconducting~~ superconducting qubit can evolve quantum mechanically when it is coupled to the resonant control system. Further, the state of the superconducting qubit can remain fixed when the resonant control system is not coupled to the superconducting qubit.

Please replace the paragraph on page 20, line 14, beginning "Some embodiments of the present invention further provide" with the following amended paragraph:

Some embodiments of the present invention further provide for entangling the states of a first superconducting qubit and a second superconducting qubit in a quantum register by coupling the resonant control system to the first superconducting qubit for a duration t_3. The third entanglement removes entanglement of the tunable resonant control system with the superconducting qubits in the entanglement operation. This ~~entanglemnt~~ entanglement operation implements a square root of SWAP logical operation, which is sufficient, along with single qubit operations, to perform quantum computing. For more details on SWAP operations, see Blais, 2001, Physical Review A 64, 022312, which is hereby incorporated by reference in its entirety.

Please replace the paragraph on page 23, line 6, beginning "In some embodiments of the present invention" with the following amended paragraph:

In some embodiments of the present invention, a system for controlling evolution of the quantum state of a superconducting qubit includes a superconducting

qubit that is capacitively coupled to a resonant control system. The superconducting qubit includes any superconducting qubit in which operations for initializing the qubit, evolving the qubit, and reading out the quantum state of the qubit can be performed. Such qubits include phase qubits and charge qubits. In other embodiments of the present invention, the superconducting qubit is inductively coupled to the resonant control system. Inductive coupling is useful for superconducting qubit embodiments where alternate fabrication methods are necessary. See, *e.g.*, U.S. patent serial number 10/025,848, entitled "FINGER SQUID QUBIT DEVICE" to ~~Tsalenchouk~~ Tzalenchuk *et al.*, filed December 17, 2001, which is hereby incorporated by reference in its entirety.

Please replace the paragraph on page 25, line 22, beginning "It is known in the art that controlled entanglement" with the following amended paragraph:

It is known in the art that controlled entanglement of quantum states of Josephson junction qubits is difficult when there is no intermediate mechanism for mediating the entanglement operation. Yet it is precisely this form of entanglement that is needed in order to build quantum computing devices that fully exploit the power of quantum computations. The problem of entangling qubits becomes more difficult when the qubits that are to be entangled are not the same type (*e.g.* phase qubit versus charge qubit). In such situations, an intermediate mechanism is typically needed. The present invention provides novel ways for entangling qubits using the resonant control system described above. That is, some embodiments of the present invention use the resonant control system as an intermediate mechanism. The resonant control system can be used both in a homogenous environment, where qubits of the same type are entangled, and a heterogeneous environment where different types of qubits are entangled. Thus, the intermediate mechanism allows for quantum heteroregisters in which different types of superconducting qubits are entangled. As used herein, a heteroregister is a plurality of qubits, wherein at least one qubit in the plurality of qubits is different than another qubit in the plurality of qubits and wherein each qubit in the plurality of qubits can be entangled with another qubit in the plurality of qubits. Thus, an advantage of heteroregisters is the ability to entangle different types of superconducting qubits, such as charge qubits, flux qubits, and phase qubits. For a review of various types of qubits, see Makhlin *et al.*, 2001,

"Quantum-State Engineering with Josephson-Junction Devices", *Reviews of Modern Physics*, 73:357, as well as U.S. patent serial number 10/025,848, entitled "FINGER SQUID QUBIT DEVICE", to ~~Tsalenchouk~~ Tzalenchuk *et al.*, filed December 17, 2001, which are hereby incorporated by reference in their entireties.

Please replace the paragraph on page 27, line 6, beginning "Readout device 650 includes junction 653" with the following amended paragraph:

Readout device 650 includes junction 653, a current source 651, a ground 652, and a voltmeter 654. Junction 653 plays the role of changing the behavior of qubit 610 to the nonhysteretic, overdamped mode. In some less preferred embodiments, junction 653 is a shunt resistor made of normal metal. In other embodiments junction 653 is a Josephson junction with a large normal conductance and small resistance. Methods for providing current source 651 are well known in the art. Current source 651 can be controlled from room temperature equipment using appropriate low-temperature filters. Methods for providing voltmeter 654 are well known in the art. In some embodiments of the invention, the leads connecting to voltmeter 654 can pass through a cold amplifier to be sampled at room temperature.

Please replace the paragraph on page 29, line 2, beginning "Readout device 650 includes junction 653" with the following amended paragraph:

The structure of a device 700 which includes a resonant control system 920 has been disclosed (Fig. 7). The structure includes an array (*e.g.*, register, quantum register) of two or more qubits 610. At least two of the qubits 610 in the register are capacitively coupled to resonant control system 920. A method for using device 700 to entangle qubits ~~620~~ 610 will now be described.

Please replace the paragraph on page 31, line 20, beginning "In Figure 8, quantum register 900" with the following amended paragraph:

In Figure 8, quantum register ~~900~~ 800 has qubit groups 802-1 and 802-2. Qubit group 802-1 includes qubits 610-1 and 610-2, resonant control system 920-1,

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and bus segment 990-1. Qubit group 802-2 includes qubits 610-3 and 610-4, resonant control system 920-2, and bus segment 990-2. Qubits 610-1 through 610-4 are respectively associated with devices 660-1 through 660-4. Each device 660 is a mechanism for controlling the quantum state of the corresponding qubit 610. In some embodiments, each device 660 controls the quantum state of the corresponding qubit 610 by providing a gate voltage or a microwave signal. For example, in one embodiment, each device 660 includes an ~~A/C~~ AC current generator 661, a charge device 662, and a ground 630_c as illustrated in Figure 7. In an embodiment of the present invention, at least one qubit 610 in Figure 8 is a superconducting charge qubit and at least one resonant control system 920 in Figure 8 is a resonant control system 620 (Fig. 7).

Please replace the paragraph on page 32, line 27, beginning "In step 1002, a switch 991 between the" with the following amended paragraph:

In step 1002, a switch 991 between the first qubit group 802 and a region 990-P that adjoins a second qubit group 802 is closed. Closure of switch 991 allows first resonant control system 920 to couple to a first pivot qubit 610-p. To achieve this coupling, resonant control system 920 is biased to a frequency $\cancel{\omega_{12}}$ $\underline{\omega'}$ that represents the energy differential between a first potential energy level and a second potential energy level (*e.g.*, the lowest two potential energy levels) of pivot qubit 610. This coupling is allowed to continue for a time period t_{1002}. The length of time t_{1002} is application dependent. In some embodiments, t_{1002} is one microsecond or less. In other embodiments, t_{1002} is one hundred nanoseconds or less. In still other embodiments, t_{1002} is ten nanoseconds or less. In any event, the length of time t_{1002} is sufficient to couple the quantum state of first resonant control system 920 with the quantum state of first pivot qubit 610-p.

Please replace the paragraph on page 37, line 8, beginning "In the present invention, in order to" with the following amended paragraph:

In the present invention, in order to utilize the qubit-qubit entanglement operation described in detail above (for the system described in Figures 7 and 8) the

interaction term in the interaction Hamiltonian that describes an interaction between the superconducting qubit and the resonant control circuit should be off-diagonal (*e.g.*, have the form H_{xy} of Equation ~~B~~ A). Thus, a system that includes a qubit of the first class described above, such as qubit 610, has the appropriate interaction Hamiltonian. In other words, the native interaction Hamiltonian for the first class of qubits supports maximal entanglement of a qubit coupled to a bus and resonant control system (*e.g.*, the configuration of Fig. 7). The native interaction Hamiltonian for the first class of qubits also supports maximal entanglement between a qubit and capacitively or inductively coupled resonant control system (*e.g.*, the configuration of Fig. 6).

Please replace the paragraph on page 39, line 1, with the following amended paragraph:

Application of a Hadamard gate, before and after tuning a capacitively or inductively coupled resonant control system (*e.g.*, creating the sequence **H** H_{zy} **H**) results in the interaction Hamiltonian:

$$\cancel{H \cdot H_{zy} \cdot H = \frac{\varepsilon_q}{2} \cdot \sigma_z^q + \frac{\varepsilon_b}{2} \cdot \sigma_z^b + \gamma \cdot \sigma_x^q \cdot \sigma_y^b = H_{xy},} \qquad \cancel{(C)}$$

$$\underline{H \cdot H_{zy} \cdot H = \frac{\varepsilon_q}{2} \cdot \sigma_z^q + \frac{\varepsilon_b}{2} \cdot \sigma_z^b + \frac{\gamma}{2} \cdot \sigma_x^q \cdot \sigma_y^b = H_{xy}} \qquad \text{(C)}$$

where the interaction term is now off-diagonal (*e.g.*, includes σ_x). Therefore, by application of a Hadamard gate before and after coupling a qubit, the present invention realizes universal quantum computation using several different types of qubits, including charge qubits, phase qubits, and flux qubits.

Please replace the paragraph on page 42, line 7, beginning "In some embodiments in accordance with this" with the following amended paragraph:

In some embodiments in accordance with this aspect of the invention, the first qubit is capacitively coupled to the bus and the second qubit is capacitively coupled to the bus. In some embodiments, the resonant control circuit is in electrical communication with the bus. In some embodiments, the recoupling operation

comprises implementing a Hadamard gate on the at least one of the first qubit and the second qubit. In some instances, the Hadamard gate comprises the sequence $Z(\pi/2)$-$X(\pi/2)$-$Z(\pi/2)$, wherein $X(\pi/2)$ is a single qubit σ_x operation and $Z(\pi/2)$ is a single qubit σ_z operation, and ~~each~~ the σ_x operation is applied over a phase evolution of $\pi/2$ and ~~the~~ each σ_z operation is applied over a phase evolution of $\pi/2$.

Please replace the paragraph on page 42, line 30, beginning "In some embodiments, the resonant control" with the following amended paragraph:

In some embodiments, the resonant control circuit is characterized by an inductance and a capacitance. In some instances, the inductance is tunable. In some embodiments, the resonant control circuit comprises a current-biased Josephson junction and the first tuning and the second tuning comprises changing a current bias across the current-biased Josephson junction. Very little change in the current-bias is required. For example, in some embodiments, the current-biased Josephson junction is changed by 1 micro-Ampere or less during the first or second tuning. In another example, the current-biased Josephson junction is changed by ~~by~~ 100 nanoAmperes or less during the first or second tuning.